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14. ABSTRACT
The transport of heat at the nanometer scale is becoming increasingly important for a wide range of nanotechnology applications. Recent computational studies on near-field radiative heat transfer (NFRHT) suggest that radiative energy transport between suitably chosen/tailored parallel surfaces increases dramatically—by about three orders of magnitude—above that predicted by the Stefan-Boltzmann law, when the gap between the surfaces is reduced to the nanometer range. In addition, the thermal surface emissions for tailored materials are predicted to be monochromatic, suggesting that these phenomena may enable ground-breaking advances in the thermal

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Report Title

Final Report: Engineering Near-Field Transport of Energy using Nanostructured Materials

ABSTRACT

The transport of heat at the nanometer scale is becoming increasingly important for a wide range of nanotechnology applications. Recent computational studies on near-field radiative heat transfer (NFRHT) suggest that radiative energy transport between suitably chosen/tailored parallel surfaces increases dramatically—by about three orders of magnitude—above that predicted by the Stefan-Boltzmann law, when the gap between the surfaces is reduced to the nanometer range. In addition, the thermal surface emissions for tailored materials are predicted to be monochromatic, suggesting that these phenomena may enable ground-breaking advances in the thermal management of micro devices and nanoscale-gap thermophotovoltaic (TPV) energy conversion devices. However, direct experimental verification of the predicted NFRHT between parallel surfaces, with nanoscale precision, has not been achieved although it is critical for additional progress. In this project we have developed a variety of tools for probing NFRHT in nanoscale gaps between nanostructured materials. This includes both scanning-probes with embedded thermocouples for near-field radiation studies and micro-devices for measuring thermal transport in nanoscale gaps in both sphere-plane and plane-plane configurations.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
12/12/2015	1.00	Kyeongtae Kim, Wonho Jeong, Woochul Lee, Seid Sadat, Dakotah Thompson, Edgar Meyhofer, Pramod Reddy. Quantification of thermal and contact resistances of scanning thermal probes, Applied Physics Letters, (11 2014): 203107. doi: 10.1063/1.4902075
12/12/2015	2.00	Bai Song, Yashar Ganjeh, Seid Sadat, Dakotah Thompson, Anthony Fiorino, Víctor Fernández-Hurtado, Johannes Feist, Francisco J. Garcia-Vidal, Juan Carlos Cuevas, Pramod Reddy, Edgar Meyhofer. Enhancement of near-field radiative heat transfer using polar dielectric thin films, Nature Nanotechnology, (02 2015): 253. doi: 10.1038/nnano.2015.6
12/12/2015	3.00	Kyeongtae Kim, Bai Song, Víctor Fernández-Hurtado, Woochul Lee, Wonho Jeong, Longji Cui, Dakotah Thompson, Johannes Feist, M. T. Homer Reid, Francisco J. García-Vidal, Juan Carlos Cuevas, Edgar Meyhofer, Pramod Reddy. Radiative heat transfer in the extreme near field, Nature, (12 2015): 0. doi: 10.1038/nature16070

TOTAL: 3

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received   Paper

TOTAL:

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(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received   Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received   Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Bai Song	1.00	
FTE Equivalent:	**1.00**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Pamod Reddy	0.00	
Edgar Meyhofer	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
1
Total Number: **1**

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

In this project we focused on understanding radiative heat transfer in nanoscale gaps between a variety of materials. It is well known that hot bodies emit energy in the form of electromagnetic waves. Understanding such thermal emissions is of great importance for numerous applications in engineering and science. From a fundamental viewpoint, the study of thermal radiation played a central role in the development of Quantum Mechanics. Max Planck successfully laid down the principles of far-field radiative heat transfer at the beginning of the 20th century. However, Planck explicitly noted that his theory was only applicable to situations where the separation between the objects involved in the radiative heat transfer is significantly larger than the wavelength of radiation with dominant contributions to radiative heat transfer (~10 μm at room temperature). The advent of micro- and nanoscience has highlighted the great importance of nanoscale radiation for several technologies including information storage (heat-assisted magnetic recording), thermophotovoltaics and nanolithography. However, experimental elucidation of nanoscale radiative heat transfer has been severely hampered by the lack of the necessary tools for systematically probing nanoscale radiation. Here, we briefly report our accomplishments that have resulted in publications in Nature and Nature Nanotechnology.

1. Quantitative Measurement of Thermal Contact Resistance and Thermal Resistance of Scanning Probes
Scanning probe techniques play an important role in understanding nanoscale energy conversion and transport. Specifically, scanning thermal microscopy (SThM) has been widely used for local measurements of temperature fields, thermal conductivity, thermopower, atomic-scale heat dissipation and even nanoscale thermal lithography. In all SThM techniques a temperature sensor (thermocouple or resistance-based thermometer), which can measure local temperatures and/or generate local heating, is integrated into the probe. Despite its wide applicability, the use of SThM for characterization of heat flows (e.g. due to radiative heat transfer) and measurement of local thermal conductivity has been limited by difficulties in quantitatively measuring the resistance to heat flow within the probe (Rp) and the resistance to heat flow at the tip-sample interface (Rc).

To overcome this problem we developed a platform, which enables accurate characterization of SThM probes by quantifying heat flows from a calorimeter into the probe. In brief, characterization of thermal resistance is accomplished by placing the scanning probe in contact with a heat-flow calorimeter that is capable of resolving heat flows with ~10 pW resolution. Upon inputting a sinusoidally modulated heat current into the suspended region of the calorimeter, the temperature of the suspended region (ΔTcal) is modulated at an amplitude that is proportional to the thermal resistance of the suspension beams. Contacting the suspended calorimeter with the tip of a SThM probe creates an additional conduction path through the probe resulting in both a heat current through the probe and temperature oscillations with amplitude ΔTP in the tip of the probe. Further, ΔTcal is attenuated due to the introduction of an additional pathway for heat conduction. For accurate calibrations we simultaneously record the amplitudes of the temperature changes in the scanning probe tip (ΔTp) and the suspended calorimeter (ΔTcal) when the probe tip is both in contact and out of contact with the calorimeter. The difference in the temperature of the suspended region with and without probe contact allows us to precisely quantify the heat flow through the probe (Qp). Further, from the measurement of ΔTp we are able to determine both Rp and Rc. These results were recently published in Applied Physics Letters1.

2. Probing the effectiveness of Thin Films in Enhancing Nanoscale Radiative Heat Transfer
In order to experimentally elucidate nanoscale radiation we custom-building sophisticated novel instrumentation, including an ultra-stable nanopositioner and several high sensitivity micro-devices, which were critical for his future research. By leveraging these instrumentation advances we first answered a key question in nanoscale radiation: How can nanoscale, radiative heat transport be controlled via ultra-thin films? Using highly original, ground-breaking experiments we were able to study near-field radiation in thin films for the first time. Impressively, we demonstrated dramatic heat transport enhancements, even for films much thinner than the penetration depth of radiation, signaling a breakdown of the Stefan-Boltzmann law for radiative heat transfer. These interesting experimental findings were analyzed by our collaborators in Spain (Prof. Cuevas and others), in terms of the spectral characteristics and mode shapes of cavity surface-phonon polaritons. Taken together, the experiments and theoretical analysis helped establish a comprehensive framework for nanoscale radiative heat transport in polar, dielectric thin films. These results, which have important implications for the creation of thermo-photovoltaic devices and novel heat management technologies, were recently published in Nature Nanotechnology2.

3. Probing Field Radiative Heat Transfer in the Extreme Near Field (Gap Sizes of 1 to 10 nm)
After successfully accomplishing the above described experiments we performed challenging experiments to establish the principles of radiative heat transfer in the extreme near–field, i.e. for objects separated by a few nanometers. In this effort, we leveraged novel microdevices and custom-developed scanning thermal microscopy probes capable of unprecedented picowatt resolution. Our experiments on radiative heat transfer in nanometer-sized gaps of polar dielectric as well as metallic materials showed—for the first time—dramatic enhancements of radiative heat transfer in the extreme near-field. Further, state–of–the–art calculations that correspond to the exact experimental conditions show that such enhancements can be modeled with great accuracy using fluctuational electrodynamics theory. Our results disproved current dogma in nanoscale heat transfer, which held that radiative heat transfer in single digit nanometer-sized gaps cannot be explained by any existing theory. Further, our work resolved a major controversy in the field and hence represents a foundational contribution to the field of heat transfer. Since the insights obtained from this work bear upon several research areas including nanoscale energy transfer, near-field thermophotovoltaics, radiative heat-assisted magnetic recording, and nanolithography this work has recently been accepted for publication in Nature3.

These advances now place us in a unique position to systematically design and exlore materials for novel novel thermal management and energy conversion applications.

References:

1. K. Kim, W. Jeong, W. Lee, S. Sadat, D. Thompson, E. Meyhofer, P. Reddy, “Quantification of Thermal and Contact Resistances of Scanning Thermal Probes” Applied Physics Letters (2014)
2. B. Song, Y. Ganjeh, S. Sadat, D. Thompson, A. Fiorino, V. Fernandez, J. Feist, F. G. Vidal, J. C. Cuevas, P. Reddy, E. Meyhofer, “Enhanced Near-Field Radiative Heat Transfer Using Polar Dielectric Thin Films” Nature Nanotechnology (2015).
3. K. Kim, B. Song, V. Fernandez, W. Lee, W. Jeong, L. Cui, D. Thompson, J. Feist, M. T. H. Reid, F. G. Vidal, J. C. Cuevas, E. Meyhofer, P. Reddy, “Radiative heat transfer in the extreme near field” Nature (2015)

Technology Transfer